# Rock /fluid interaction during induced earthquakes: Where does frictional heat go?

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## Introduction

Earthquakes occur because faults weaken during sliding. The exact role of pore fluids on fault weakening mechanisms is still under debate. In dry conditions, one of the main candidates for fault weakening is the Flash Heating mechanism [Rice, 2006] which results from thermal degradation of fault asperity contacts when enough frictional power is dissipated during seismic slip. Nevertheless, faults are rarely dry. Theoretical models predict that in presence of water shear heating can trigger thermal expansion of fluids trapped in faults, leading to a dramatic reduction of fault strength [Rice, 2006]. Such weakening mechanisms are activated on the bulk fault surface when temperatures rise in faults during seismic slip but seem to occur at very different spatial scales. It is therefore of major importance to study how heat is distributed between fluids and fault rocks during earthquakes at both: (1) microscopic scale (i.e at fault contacts) and (2) the macroscopic scale (i.e bulk fault) in order to understand the influence of fluids on fault weakening and earthquake propagation. Such results might shed light on induced earthquake mechanisms.

### *Microscopic scale: The asperity flash temperature model*

We consider the microphysical interactions between highly stressed fault asperity contacts and fault water that interacts thermally with them (Geometry in figure 1.b). Such investigation will be done through an analytical model of a modified flash heating theory [Violay et al, 2014] derived from a heat balance at the contact level such that:

$$T_{flash} = \left( \frac{1}{\rho . c_p . \sqrt{\kappa . \pi}} \right) \left( \tau c . v . \sqrt{t_c} - \frac{V_w . \rho_w(P,T)}{t_c . \pi . r^2} . \left( T . c_{pw}(P,T) + L_w(P,T) \right) . \sqrt{t_c} \right)$$

$$(1)$$

Where $\rho . c_p$ is the solid's specific mass capacity, $\kappa$ is the rock's thermal diffusivity, $\tau c$ is the shear stress at the contacts, $v$ is an arbitrary imposed slip velocity and $t_c$ is the lifetime of the contacts. Vw is the interacting water volume such that $V_w = h . \pi . ((r + r_{th})^2 - r^2)$ with $h$ the heated asperity height; $r$ the asperity radius, $r_{th}$ the diffusion length. Then, $\rho_w(P,T)$; $c_{pw}(P,T)$, and $L_w(P,T)$, are respectively water's density, specific heat, and latent heat which are dependent on pressure and temperature [NIST Chemistry WebBook].
Here, the driving stress is the penetration hardness of asperities.

Under dry conditions (Figure. 1.a, red curves), when no buffering takes place, the flash temperature rises as a power law of slip. The expected lash heating temperature (approximately 1000 ˚C) was reached for slip rates >10 cm.s⁻¹ during the asperity lifetime, as predicted by Flash Heating theories and experiments. For such velocities, when pore pressures are lower than 22 MPa, the temperature rise is buffered in the first half of the contact lifetime, and so, flash temperatures remained lower than vaporization temperatures, i.e., while water stayed in a liquid state. Longer slip (and so, higher shear heating and larger power dissipation) allowed water to overcome the liquid-vapour phase transition temperature during $t_c$, inducing a strong drop in $\rho_w$ and $c_{pw}$ (roughly falling to 0.5% and 50% of their room temperature values respectively; Fig. 1c,d), thereby enhancing shear heating at contacts and leading to flash temperatures similar to those of dry conditions. Conversely, at fluid pressures ranging from 25 to 70 MPa, temperature rises are delayed by water cooling during $t_c$ due to the liquid-supercritical transition. This phase change requires larger amounts of energy because the heat capacity of water increases by 1400% during the transition at $pf$= 25 MPa (Fig. 4c) while the drop in density is smoother than in the case of vaporization. There, water becomes an extremely efficient energy buffer, reducing the efficiency of FH and hindering rises in temperature higher than that of the liquid-supercritical phase transition (~373 ˚C at $pf$=25 MPa, Extended Data Figure 7) at asperity contacts during their lifetime, even for slip rates of 1 m.s⁻¹ (admitted slip rate during regular earthquakes).

## Macroscopic scale: Bulk fault temperature model

We investigate the effect of shear heating on fault weakening by thermal pressurization of fault fluid using a finite difference numerical model for bulk fault heating and thermal pressurization of fault fluid modified from Rice [2006] and Chen et al. [2017b]. In the geometry presented in figure 1.b, the energy balance and mass conservation equations in the fault follow respectively:

$$\frac{\partial T}{\partial t} = \frac{1}{(\rho b.cb)}.\tau.\left(\frac{v}{wsz}\right) + \alpha th.\frac{\partial^2 T}{\partial y^2} \qquad (2) \qquad and \qquad \frac{\partial p}{\partial t} = \frac{\lambda f - \lambda n}{\beta f - \beta n}.\frac{\partial T}{\partial t} + \alpha hy.\frac{\partial^2 p}{\partial y^2} \qquad (3)$$

Where T denotes temperature of the bulk fault, $\rho b.cb = (1-\varphi).(\rho.cp) + \varphi.(\rho w.cpw)$ is the bulk fault's specific mass heat capacity, $\varphi$ is the slip zone porosity, $\rho.cp$ is the solid's specific mass heat capacity, $\tau$ is the macroscopic fault shear stress, $v$ is an arbitrary imposed slip velocity and $wsz$ is the thickness of the slip zone. $\alpha th$ is the fault's thermal diffusivity. $\alpha hy$ is the hydraulic diffusivity of the fault. $\lambda f$ and $\lambda n$ are respectively the isobaric thermal expansion coefficients of the fluid volume and of the solid pore space. $\beta f$ and $\beta n$ are respectively the isothermal compressibilities of the fluid volume and the solid pore space. All thermophysical fluid properties evolve with pressure and temperature [NIST Chemistry WebBook]. Here the driving force for the heat source term is the macroscopic fault's shear stress.

At crustal depths representative of induced seismicity (~2 to 5 km depth), the reached temperatures are not high enough to reach a flash heating temperature. Nevertheless, the heat buffer effect due to the liquid-supercritical transition is still observed for initial pore pressures higher than 22 MPa and a strong temperature rise in the fault due to water vaporization takes place in a similar manner than for the flash temperature computations, confirming our observations at the asperity scale. Since the fault's stress obeys the effective pressure law, we observe an initial fast decay in friction due to TP. The decay then stabilizes leading to friction drops of ~0.1 for slips of ~20 to 150 μm in all fluid pressure conditions. Therefore, at High_Pf, TP might well be the dominant weakening mechanism while at low fluid pressures, flash heating should be more efficient during induced earthquakes.
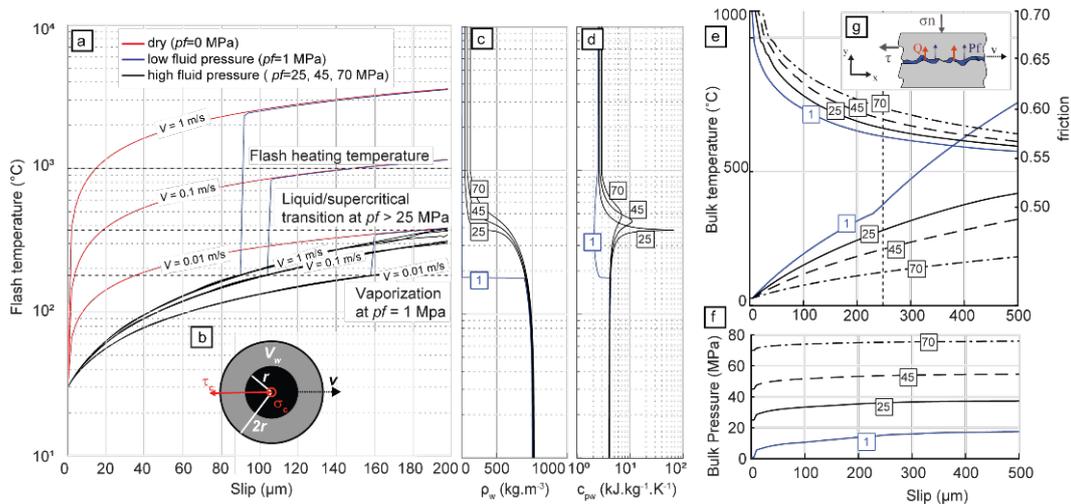


**Figure. 1. a-d. Flash temperature computation. (a)** Flash temperature at the asperity contacts versus slip **(b)** Contact geometry. **(c)** Temperature versus water density **(d)** Temperature versus water specific heat. **e-g. Bulk fault shear heating.** **(e)** Bulk temperature (left y-axis) reached in the fault during shear heating and the corresponding friction evolution due to TP (right y-axis) versus slip. **(f).** Fluid pressure evolution during shear heating versus slip. **(g)** Considered bulk fault geometry

## Discussion and conclusions

Our results open perhaps the door to designing new injection strategies that account for fluid thermophysical properties dependence on temperature and pressure so that the injected fluid can act as a heat buffer during induced earthquakes, limiting slip and stress drops. A Parametric study of such models might reveal controls of weakening mechanisms.

## References

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